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Isolated deep earthquakes and the fate of subduction in the mantle

Paul Lundgren
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Domenico Giardini
Istituto Nazionale di Geofisica, Rome, Italy

Abstract. The locations of earthquakes with depth in the mantle provide direct evidence of the trajectory and state of stress of subducting lithosphere. The occurrence over the last decade of isolated large deep earthquakes outside the main Wadati-Benioff zones in the Kurile, Izu-Bonin, and Chile deep seismic areas (in addition to the observed flat distributions of deep seismicity beneath the Banda Sca and Fiji Plateau areas and the large number of deep earthquakes located away from the main slab in the Tongs arc) supports recent tomographic and other seismological studies, leading to a reconsideration of slabs as simple planar structures sinking undeformed into the lower mantle. The focal geometries of these isolated earthquakes, which often exhibit near vertical compressional stresses, are distinct from adjacent events in the main Wadati-Benioff zone. They are also different in orientation from events in the deflecting toe of the slab and from the stress orientation expcctcd if the deflected slab acts as a stress guide. These isolated mantle earthquakes are interpreted to take place in subducted lithosphere that has deflected to a horizontal posture at the base of the upper mantle. Conversely, the deep seismicity in the adjacent Wadati-Benioff zone is associated with the deflection of the subducting lithosphere.

Introduction

Deep earthquakes provide direct evidence of rhe recycling of lithosphere down into the mantle to depths of at least 670 km and indicate the presence of relatively cold temperatures and high deviatoric stresses. The morphology of these Wadati-Benioff zones of deep seismicity and the focal mechanisms of individual earthquakes identify planar lithospheric structures in downdip compression everywhere below about 300 km depth [*Isacks and Molnar*, 1971; *Burbach and Frohlich*, 1986].

The three main characteristics of deep earthquakes, their relative maximum in number and downdip compressional moment release [*Chung and Kanamori, 1980*], above their absolute cessation at 650-700 km [*Stark and Frohlich*, 1985; *Rees and Okal*, 1987], have been argued as evidence that deep slabs do nor penetrate deeper than 700 km [*Richter*, 1979] or have been-explained as a combination of temperature-pressure-rheology effects in a subducting lithosphere possibly extending into the lower mantle [*Wortel*, 1986; *Goto et al.*, 1987; *Wortel and Vlaar*, 1988; *Ito and Sato*, 1991; *Kirby et al.*, 1991]. Indeed, the depth of the subduction cycle and whether there exists a stable boundary layer at 670 km depth separating a stratified mantle structure are among rhe outstanding problems in geophysics.

A physical mechanism (transformational faulting) has recently been proposed for the generation of deep earthquakes [*Kirby, 1987; Green and Burnley, 1989; Kirby et al.,* 1991]. It reproduces the fault like dislocation and seismic emissions required of earthquake radiation patterns, and tits closely with the existence of stable faults observed in deep slabs [*Billington and Isacks*, 1975; *Giardini and Woodhouse, 1984; Lundgren and Giardini*, 1992]. This mechanism reflects the ambient state of stress and dots nor clarify the source of compressional stress in deep slabs nor resolve rbe debate over the fate of subducting lithosphere.

Recent tomographic modeling [*Van der Hilst et al.*, 1991; *Fukao et al.*, 1992] shows flat distributions of fasr velocity anomalies extending beyond the seismically active portions of the Imr-Benin, Honshu, and southern Kurile subducting slabs, interpreted as remnant lithosphere deflected at 670 km depth; in contrast, these tomographic studies find the continuation of fast velocity anomalies inro rbe lower mantle below the Indonesian, Marianas, and northern Kuriles slabs, suggesting penetration of these slabs into the lower mantle. While previous detailed analyses have elucidated the modes by which deep earthquakes accommodate this deflection [*Giardini and Woodhouse*, 1984; *Lundgren and Giardini*, 1992], questions remain as to why remnant lithosphere is nor seismically active, and if it is, what is its characteristic state of stress.

In recent years, well-located deep earthquakes have occurred ourside the known Wadati-Benioff zones in the Kurile, Izu-Bonin, Tongs, and Chile regions [*Okino et al., 1989; Ekström et* al., 1990; *Sipkin, 1990; Giardini*, 1992; *Glennon and Chin, 1993*]. These are usually large earthquakes located 100300 km from rhe nearest deep seismicity, wirh focal geometries whose orientation does not fit with the dip-parallel compression in the adjacent slab, nor with the stress-guide concept, which would predict nearly horizontal compressive stresses in subducting slab rotated to horizon-

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tal. In addition to these isolated earthquakes, extended horizontal distributions of seismicity for up 101000 km at 600 km depth are known to exist beneath the Banda Sea and Fiji Plateau [*Hanus and Vanek, 1978; Chiu et al., 1991*], the two areas in the world where the geometries of the surrounding subduction zones and the relative plate velocities concentrate subducted lithosphere into the same area in the mantle. The first observations of deep earthquakes outside slabs were explained in terms of detached lithosphere or remnants of complex and rapidly evolving subduction environments [*Hanus and Vanek, 1978; Hamburger and Isacks, 1987*]. However, the occurrence of these events over the last 10 years in most subduction zones, spanning the whole spectrum of subduction regimes, shows them to be a more general feature of the subduction cycle.

We present a survey of isolated deep earthquakes from several circum-Pacific subduction zones. In this study, '(isolated" is intended to mean located away from the the main downdip Wadati-Benioff zone seismicity in the direction of subduction. In this definition we are not considering the majority of deep seismicity in subduction zones such as South America and Java where there are large gaps of 200–300 km in the intermediate-deep seismicity in the plane of the slab. Tbe goal of (his study is to understand these isolated earthquakes in the context of mantle dynamics. We find that when viewed as a whole these events demonstrate not only cases of slab deflection in many deep subduction zones but also focal geometries consistent with vertical compressive stresses in remnant lithosphere capable of generating large earthquakes.

Data and Projections

We use seismicity locations taken from the international Seismological Centre ([SC) catalogue (1964 1989); we do not relocate the seismicity since we are looking at macroscopic effects and the locations of the anomalous earthquakes are known with sufficient precision (10-20 km) to identify them as isolated. We use focal mechanism solutions derived from Harvard centroid moment tensor (CMT) solutions [*Dziewonski et al.*, 1981] (from the quarterly reports in *Physics of the Earth and Monetary Interiors*). This catalogue of focal solutions covers the years 1977-1992,

Our first goal is to characterize the focal mechanisms of deep earthquakes in relation to those observed in active deep slabs. For this purpose we look at two-dimensional cross sections of subduction zone seismicity and CMT P axes. This allows us to compare the component of compression in the plane parallel to the direction of slab subduction and to highlight the differences between the stress geometry of the isolated events and the prevailing downdip compression in the Wadati-Benioff zone. This type of projection emphasizes forces in the direction of subduction. For each focal mechanism the amount of compression out of the plane of the cross section is proportional to the length of the line representing the P axis: the shorter the line, the more oblique the P axis orientation with respect to the cross section plane. We also compare moment tensors for characteristic isolated events and for typical downdip compressional events in the subducting slab. The availability of moment tensor solutions allows us to make considerations on the percentage of moment release for isolated versus main slab seismicity. Finally, we apply a statistical method for comparing the relative orientations of the main slab and isolated deep earthquake P axes with respect 10 the downdip and normal axes of the local slab geometry [*Frohlich and Willemann, 1987; Apperson and Frohlich, 1987*].

In Figure 1 we show maps of the subduction zones presented in this study with their seismicity and in Figure 2 we show. the locations of the vertical cross sections. We also indicate the relative direction of convergence of the subducting plate in each cross section at each subduction zone using the NUVEL-1 global plate motion model [*DeMets et al.*, 1990]. In general, the plate convergence direction is perpendicular to the strike of the subduction zone, shown in Figure 2.

Isolated Deep Earthquakes

The maps in Figure 1 show the locations of earthquakes in the circum-Pacific subduction zones where we find isolated deep earthquakes. Cross sections of the seismicity and P axes are shown in Figure 2 for the Kurile (cross section A), Chile (cross section B), Izu-Bonin (cross section C), Banda (cross section D), Tonga (cross section E), and Fiji areas (cross section F), which are described below.

Cross Section Descriptions

Cross section A. At the Kurile trench the Pacific plate subducts beneath the Eurasia plate. This has been an area of much study regarding the shape of the descending slab, its state of stress, and its fate at the 670 km seismic discontinuity [e.g., *Stauder and Mualchin, 1976; Creager and Jordan,* 1984, 1986; *Silver and Chan,* 1986; *Burbach and Frohlich, 1986; Lundgren and Giardini, 1990; Zhou and Clayton, 1990; Schwartz et al.,* 1991; *Van der Hilst et al., 1991; Fukao et al., 1992; Glennon and Chen, 1993*]. The curvature of the southern Kurile arc gives a range of cross-section profile azimuths which maybe drawn. The largest deep earthquake in the last 15 years (M_0 = 8.2 x 10^{26} dyn cm) occurred on May *12, 1990*, 150–200 km away from the main concentration of deep seismicity [*Ekström et al.*, 1990; *Sipkin*, 1990]. The projection of its compressional axis is subvertical and distinct from the more shallowly plunging compressional axes in the main slab.

Cross section R. The Wadati-Benioff zone in the Chile cross section shows the trajectory of the Nazca plate beneath South America. On February 28, 1989, a moderate sized, isolated earthquake occurred some 150 km to the east of the main cluster of deep seismicity. This isolated event features a near vertical P axis, in marked contrast to the main cluster of deep earthquakes which have P axes parallel to the subduction flow.

Cross section C. In the Izu-Bonin subduction zone the Pacific plate subducts to the west beneath the Philippine plate. The Wadati-Benioff zone is marked fry a dense concentration of activity, the second most productive deep area in the world. At 500 km depth both hypocenters and }' axis geometries show a bending of the Wadati-Benioff zone 10 a horizontal posture. This pattern is accentuated try the location of the July 4, 1982, earthquake, the largest in the area (M_0 = 1.3 x 10^{26} dyn cm), at over 200 km west of the main Wadati-Benioff zone at a depth of 550 km [*Okino et al., 1989*]; the projection of its P axis is near vertical.

Cross section D. The Banda subduction zone is part of a complex and rapidly evolving tectonic regime. The Wadati-Benioff zone is characterized at depth by a sharp curvature

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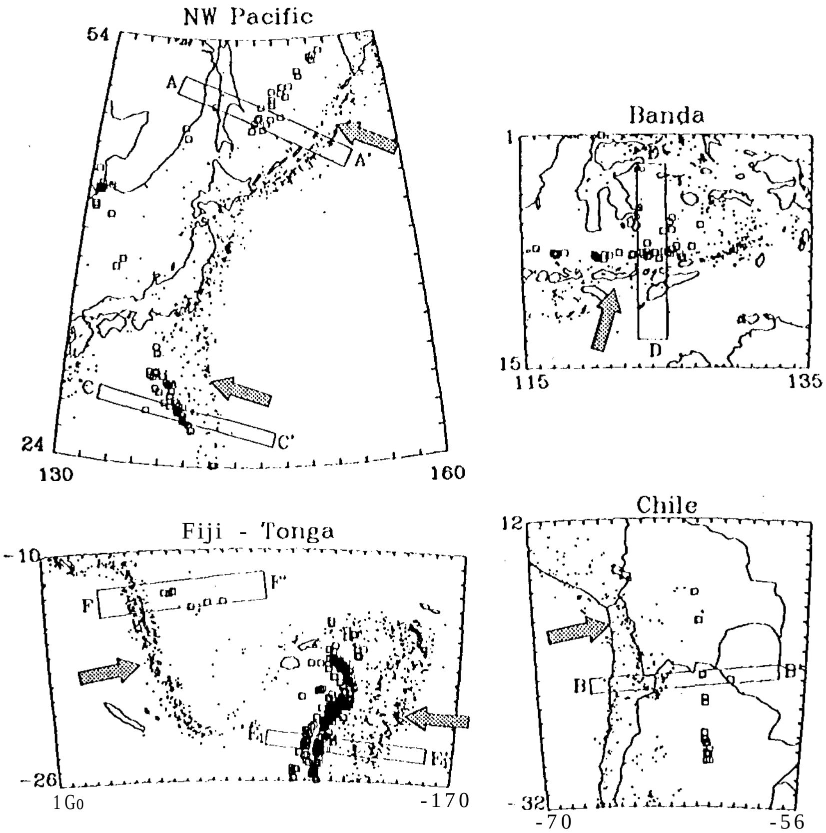

Figure 1. Map views of the subduction zones presented in this study. Small dots represent epicenters of earthquakes shallower than 400 km depth; squares are earthquakes deeper than 400 km, all from the CMT catalogue. Locations of cross sections shown in Figure 2 are also shown. A, Kuriles; B, Chile; C, Izu-Bonin; D, Banda; E, Tonga; and I, Fiji Plateau. Shaded arrows give the relative motion direction of the subducting plate and the overriding plate at each subduction zone [*DeMets et* al., 1990].

and a flat distribution of deep earthquakes over an area 500 x 300 km [*Cardwell and Isacks*, 1978; *Chiu et* al., 1991]; a result of the confluence of subduction flows from the south (Australia) and east (Pacific) beneath Eurasia [*DeMets et al.*, 1990]. We present a N-S cross section viewed from the east, showing the Australian plate subduction, Several events occur outside the main Wadati-Benioff zone; the largest two are located about 150 and 300 km to the north, with a subvertical *P axis*, and the other with an intermediate plunging P axis distinct from the main slab events 300 km to the south. A similar picture is obtained with an E-W section parallel to the direction of flow from the Pacific.

Cross section E. In the southwest Pacific the Pacific plate subducts to the west beneath the Australian plate at the Tonga trench. This subduction zone represents the most active region of deep seismicity in the world. The section E_1 presents a view from the south across the southern portion of Tonga, where the deep seismicity forks into two separate, parallel bands, indicating defection of the subducted lithosphere to a horizontal posture [*Giardini and Woodhouse, 1984]*. The enlargement of the deepest portion of this section (E_2) shows that the projected *P* axes in the two clusters have distinctly different geometries. The group to the east is dominated by down-dip compression, although the dips of the P axes are consistently shallower, by 10°-20°, than the trajectory of the subducting lithosphere through the mantle (compare sections E_1–E_2); the western group instead is composed almost exclusively of events with subvertical *P* axes oriented perpendicular to those of the eastern group [*Giardini, 1992]*.

Cross section F. The horizontal distribution of seismicity lying along the base of the upper mantle below the Fiji Plateau [*Brocher*, 1985; *Hamburger* and *Isacks*, 1987] is the result of the subduction of the Australia plate and rollback of the New Hebrides trench from the west and of the fast subduction and rollback of the Pacific plate at the Tonga trench, along with Pacific plate material that was subducted at the now inactive Vityaz trench [*Billington*, 1980; *Giardini*

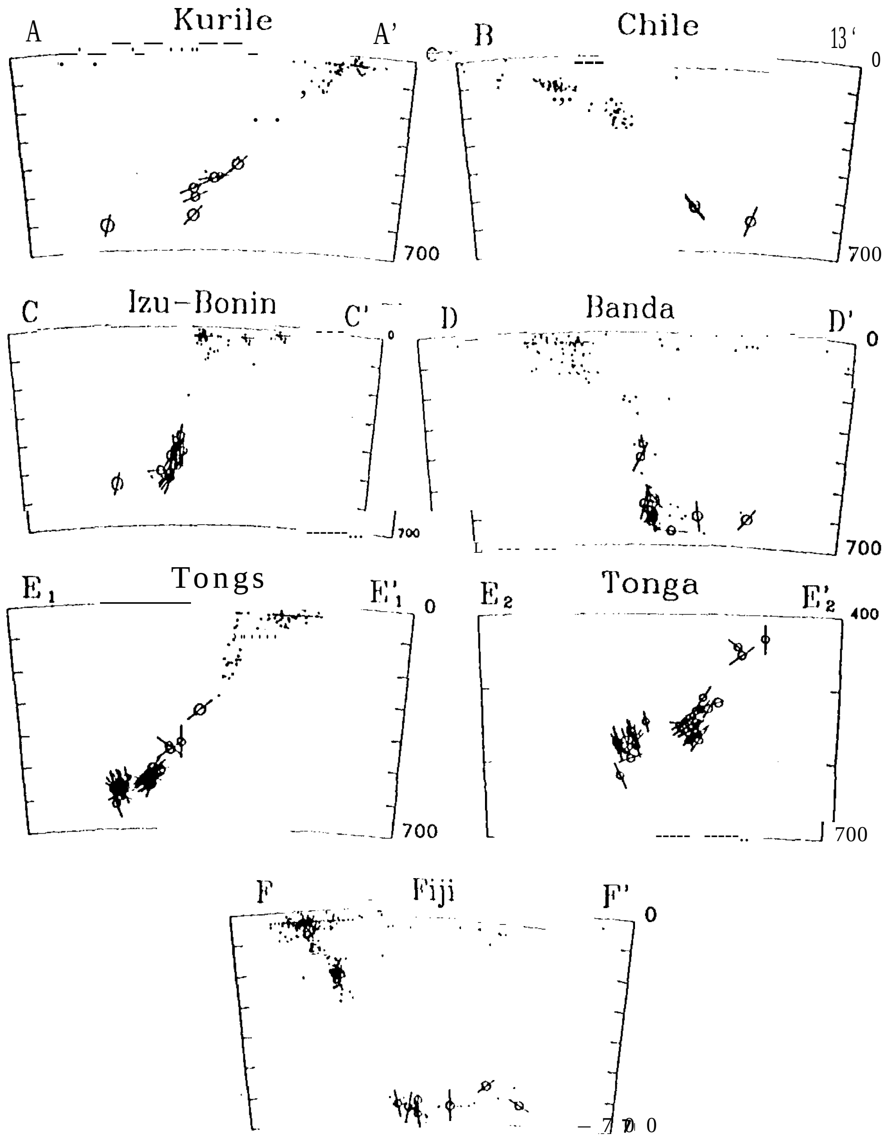

Figure 2. Vertical spherical cross sections through each of the subduction zones shown in Figure 1. The radial axis is from the surface to 700 km depth. We plot CMT solutions with the event location given by (he circle, which has a size proportional to the magnitude of the earthquake. The projection of the compressional (P) axis given by the bar. The length of the bar is directly proportional to its orientation with respect to the plane of the cross section. Where seismicity is shown $m_b > 4.5$, except in B-B' and C-C' where the threshold used is 4.8. A-A' Kurile cross section of 1.3° width with endpoints located at (50.6°N, 138%) and (45.2°N, 155%). B-B' Chile cross section of 1" width with endpoints at (23.5°S, 72°W) and (22.5°S, 58°W). C-C' Izu-Bonin cross section of 1° width with endpoints at (28.9°N, 133°E) and (25. 9°N, 147°E). D-D' Banda cross section of 2° width with endpoints al (13"S, 124°11) and (1"S, 124°E). E_1-E_1' Tongs cross section of 1" width with endpoints located at (23"S, 176°E) and (24°N, 172°W). E_2-E_2' close up of Tonga cross section of 1° width with endpoints located at (23.2°S, 178.2°E) and (23.5°N, 179.2W). ~~F Vertical cross sections~~ across the Fiji Plateau spanning the (left) New Hebrides and (right) Tonga subduction zones. F_1-F_1' 2° width with endpoints located at (13.5°S, 164°E) and (12.5°N, 176°E). ~~F_2-F_2' 1° width with endpoints located at~~ {1 S%, 164°E) and (18°N, 172°W) ← delete

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and Woodhouse, 1986; *Hamburger and Isacks*, 1987]. Cross section F is taken perpendicular to the New Hebrides arc and is viewed from the south. In the cross section the cluster of events in the densest area of seismicity directly beneath [he downdip extension of the New Hebrides slab features near-vertical compression, consistent with the steep dip of the slab trajectory and consistent with a slab detachment or a continuous slab with a seismicity gap al intermediate depth [*Brocher, 1985; Hamburger and Isacks, 1987; Chatelain et al., 1993*]. Three additional events with CMT solutions, however, lie in the extended region of deep seismicity at the base of the upper mantle. The two more distant events have P axes which are not vertical, while the third event, located 100–200 km from the main cluster of "slab" events, has a vertical compressional axis.

Focal Geometries

In Figure 3 we plot typical slab and isolated CMT focal mechanisms from each area. For each pair the main stab (h > 500 km, except for the Izu-Bonin main slab event which is at 475 km depth) event is *on* the right, and the isolated event is on the left. Each pair has been rotated about a vertical axis such that the top of the page for any given pair is the direction parallel to the strike of the subducting slab dipping to the left in Figure 3. In this way, typical events representative of each area of deep seismicity will look very similar to each other and differ only in the dip of the *P* axis, which identifies the characteristic dip of each slab trajectory. Except for the Banda events, where the vertical subduction of the slab produces a main slab focal geometry similar to the isolated event geometry, and Kurile, where the focal geometries are not that different, the isolated events have focal geometries which are significantly different than the main slab focal geometries.

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In the case of the Kurile and Chile subduction zones the isolated event focal mechanism geometry differs from the. main slab focal mechanisms by a rotation about an axis parallel (o the strike. of the slab. For the Fiji and longs slabs the isolated event focal mechanisms have nodal planes oriented perpendicular to the strike of the slab arid *vertical P axes*. The Izu-Bonin isolated event has a focal mechanism which fs completely different than any of its corresponding main slab events and may reflect complexities in the deviatoric stress produced by the along-strike change in dip of the Izu-Bonin slab and the complex modes of deformation found in this slab [*Lundgren and Giardini, 1992*].

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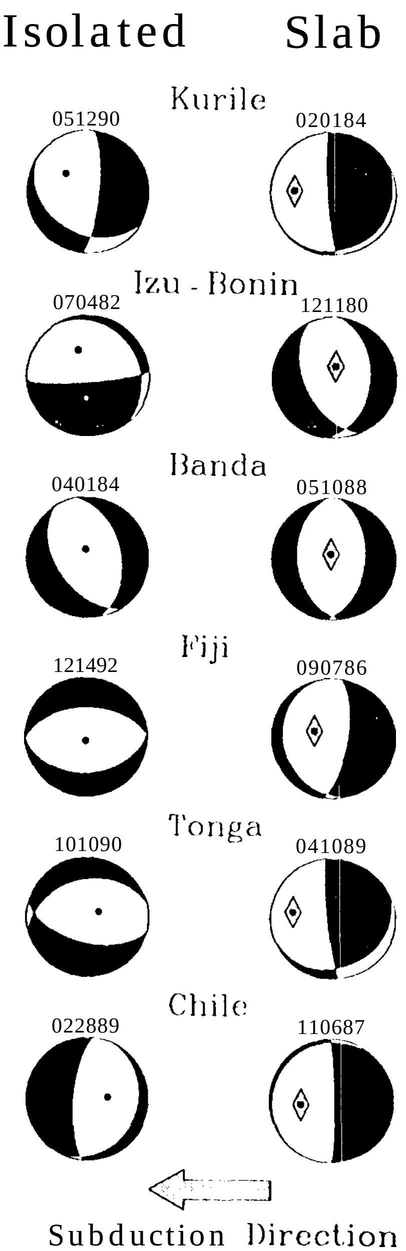

Figure 3. (opposite) Map views of lower focal hemispheres of Harvard CMT solutions for individual events whose date is given above each mechanism. Black represents compressional first motion arrivals, white dilatational arrivals. The dot in each the white quadrant represents the intersection of the compressional *(P)* axis on the lower focal hemisphere. For each subduction zone wc show "main slab" and isolated earthquakes which have typical focal mechanisms for that subduction zone, Each pair is rotated about a vertical axis such that the strike of the subducting slab is to the bottom of the page and the slab dips toward the left. Gray shaded diamond for each main slab event highlights the dip of that

Table 1. Summed Scaler Moments M_0 of CMT Solutions for Main Slab and Isolated Deep Earthquakes Deeper Than 500 km

Subduction Zone	M_0, dyn cm Main Slab	M_0, dyn cm Isolated	Percent of TOtal M_0 in Isolated Events
Kurile	3.0 x 10^{26}	8.2 X 10^{26}	73
Izu-Benin	3.0 x 10^{26}	1.3 x 10^{26}	28
Banda	9.2 X 10^{26}	4.9 x 10^{25}	5
Fiji	3.8 X 10^{24}	8.9 X 10^{24}	70
Tooga	2.9 X 10^{26}	1.2 x 10^{26}	30
Chile	1.6 X 10^{27}	7.2 X 10^{25}	4

Also computed is the percentage of the total deep moment release contributed by the isolated earthquakes. For the Tongs arc the events used are only those shown in the Tongs cross section in Figure 1. For (he Chile and Banda arcs this covers only earthquakes shown in their respective map areas shown in Figare 1. For the Kurile, Izu-Bonin, and Fiji areas CMT solutions for the whole arc deeper than 500 km arc used, thus for Kuriles all events between 47" and 54°N, and for Izu-Bonin all events between 25" and 34°N, and for Fiji all the. deep CMTs are in the cross section shown in Figure 1.

Isolated Versus Main Slats Moment Release

Despite the often low occurrence rate for isolated earthquakes in many subduction zones, they may comprise a significant amount of the cumulative moment release in a given subduction zone. In Table 1 we show the cumulative scalar moment release in the subduction zones with isolated earthquakes and compare the relative summed scalar moments (M_0) of the main slab events and the isolated events for earthquakes deeper than 500 km from the CMT catalogue. Since this covers a time apan of only 15 years, the summed M_0 are dominated by a few large events in many instances, and a very large time span would be needed to accurately characterize the actual partitioning of M_0. However, what this dots show is that for marry subduction zones (i.e., Kurile, Izu-Bonin, Tonga) a significant percentage of the total scalar moment is contained in the isolated events. Other isolated deep earthquakes have occurred in previously quiet areas beneath Spain in 1954 [*Chung and Kanamori*, 1976] and Colombia in 1970 [*Mendiguren*, 1973; *Gilbert and Dziewonski*, 1975; *Furumoto and Fukao*, 1976; *Furumoto*, 1977; *Okal and Geller*, 1979]; the latter had a moment release roughly equal 10 the combined deep seismicity moment release of the last 15 years.

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Statistical Comparison of the 1' Axes Orientations

in addition to fundamental constraints on subduction geometry imposed by the hypocenter locations and the orientation of compressional axes presented in Figure 2, we apply some graphical and statistical methods to quantify the differences in compressional axes orientations between the main slab and isolated earthquakes with respect to the downdip and normal slab direction [*Frohlich and Willemann*, 1987; *Apperson and Frohlich*, 1987]. The results of these methods support what we see in the cross sections, quakes are significantly different from the downdip directions of their respective slabs.

We plot the observed main slab and isolated CMT focal mechanism P axes on a quarter of a equal-area lower hemisphere projection (Figure 4a). In this plot the P axes have been rotated such that the along-strike (AS) direction, defined as the direction perpendicular to the cross-section traces in Figure 1, is at the top of the eqaal-area plot and the downdip (DD) direction, based on the apparent dip of the Wadati-Benioff zone from the cross sections in Figure 2, points vertically down. For each group of earthquakes, main slab and isolated, Anderson-Darling plots show the actual distribution of the P axes away from the downdip direction (Figures 4b and 4c), and the axis normal to the slab (Figures 4d and 4e), as a function of solid angle. The Anderson-Darling statistic W_n^2 is used as a measure of their deviation from an isotropic dist ribution [*Frohlich and Willemann*, 1987]. In each of the Anderson-Darling plots an isotropically distributed set of axes would form a line near the diagonal line and have an W_n^2 value near 1. For an isotropic data set, W_n^2 will exceed 3.89 no more than 1% of the time [*Apperson and Frohlich*, 1987].

We apply these methods to earthquakes greater than 400 km depth in the Kurile, Chile, Izu-Bonin, Banda, and Tongs areas previously presented. For each cross section we use separate downdip directions (from Figure 2) for the main slab and the deflected toe of the slab. Thus for Kurile the main slab and isolated downdip angles are 48", and 15° respectively. For the other subduction zones the main slab and isolated event downdip angles are Chile 50°, 12"; Izu-Bonin 83", 0°; Banda 82°, 0°; Tonga 55°, 15". By rotating each group of P axes, main and isolated for each subduction zone, sach that the downdip direction for all earthquakes is vertical on the equal-area projection, we can plot all the P axes together [*Frohlich and Willemann*, 1987].

Figure 4a shows the main slab and isolated earthquake P axes folded into a quarter hemisphere equal-area projection. We sec that the main slab events have P axes that cluster toward the downdip direction, while the isolated event P axes are mostly distributed toward the perimeter at a high angle from the derived subhorizontal downdip directions of the deflected portions of these slabs. in Figures 4b and 4c we show the Anderson-Darling plots for the P axes plotted in Figure 4a, and we see that troth groups have P axes clustering that is statistically significant from a random distribution. The Anderson-Darling statistic W_n^2 of 109 for main slab P axes cluster near the downdip direction, while the isolated P axes are distributed far from the downdip direction. Figures 4d and 4e shows Anderson-Darling plots relative to the normal axis (N). Here we see that the main slab event P axes plot far from the normal axis, white the P axes of the isolated events cluster near the normal axis of their deflected slabs, with a statistically significant W_n^2 of 51. From these statistical analyses of the P axes we observe that the main slabs are in downdip compression and the deflected slabs are in compression normal to their subhorizontal orientation.

Discussion and Conclusions

The worldwide occurrence of isolated deep earthquakes

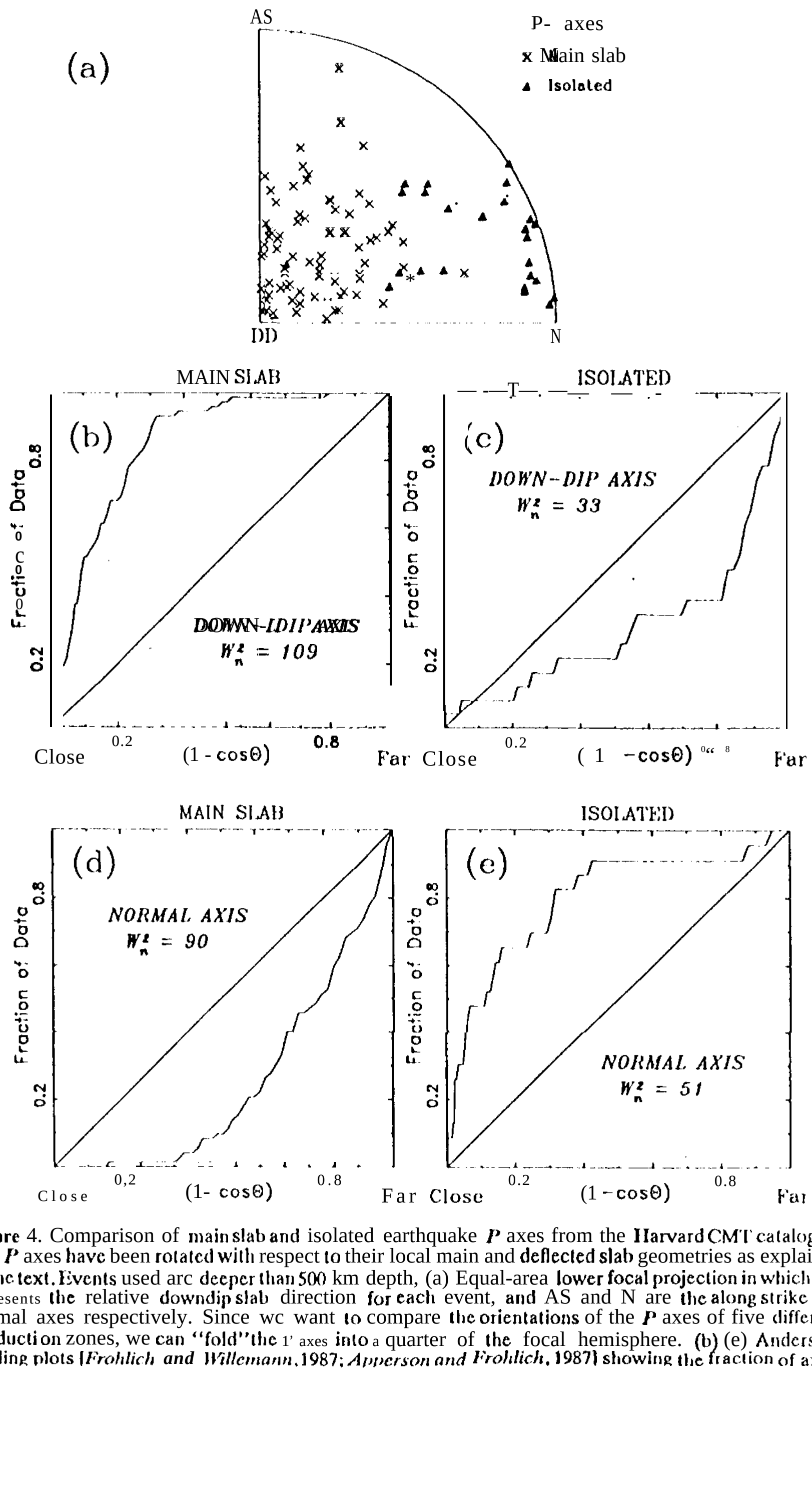

Figure 4. Comparison of main slab and isolated earthquake *P* axes from the Harvard CMT catalogue. The *P* axes have been rotated with respect to their local main and deflected slab geometries as explained in the text. Events used are deeper than 500 km depth, (a) Equal-area lower focal projection in which DD represents the relative downdip slab direction for each event, and AS and N are the along strike and normal axes respectively. Since we want to compare the orientations of the *P* axes of five different subduction zones, we can "fold" the P axes into a quarter of the focal hemisphere. (b) (e) Anderson-Darling plots [*Frohlich and Willemann*, 1987; *Apperson and Frohlich*, 1987] showing the fraction of axes

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to a horizontal posture by its interaction with the boundary between the upper and lower mantle and may extend along the bottom of the upper mantle for several hundred kilometers beyond the main Wadati-Benioff zone seismicity, in agreement with recent tomographic studies [*Kamiya et al.*, 1988; *Zhou and Clayton*, 1990; *Van der Hilst et al.*, 1991; *Fukao et al.*, 1992] and in agreement with studies of deep faulting patterns [*Giardini and Woodhouse*, 1984; *Lundgren and Giardini*, 1992].

The areas with the largest horizontal distributions of seismicity at over 600 km depth, Banda and Fiji, are the two places where complexity in the plate motions and trench geometries at the surface produce converging subduction flows which favor the accumulation of cold lithospheric material. The most active area of deep seismicity outside the main Wadati-Benioff zone, Tonga, is where the relative rate of convergence at the trench is the highest in the world [*Pelletier and Louat*, 1989; *Bevis et al.*, 1991] (> 15 cm/yr) and the subducting lithosphere among the oldest [*Engebretson et al.*, 1991]. In less complex subduction geometries, the deflection of subducting lithosphere is also confirmed by the shallowing of compressional axes as the slab interacts with the base of the upper mantle. in Izu-Bonin there is a rotation of the *P* axes from vertical at 400 km depth toward shallow and horizontal at over 500 km depth, followed by the steeply plunging *P* axis of the isolated" event. In other relatively simple subduction zoneses (Kuriles Chile and South Tonga) the isolated earthquakes have distinct *P* axis orientations compared to their main slab earthquakes which follow the shallower dip of the slab.

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The occurrence of isolated deep earthquakes in subduction zones with simple geometries (Kuriles, Izu-Bonin, Chile) indicates that the high seismic activity and state of compression in deep Wadati-Benioff zones, immediately above the point where they reach the base of the upper mantle, is associated with deflection; once this deflection has taken place, the material is no longer subject to compression in the plane of the reclined lithosphere, as indicated by the predominance of vertical P axes for isolated events. The transition from downdip compression in the Wadati-Benioff zone to vertical *compression in the deflected slab* takes place over distances less than 100 km, as shown for Tonga. Deviations from near vertical compression are so far confined 10 areas, such as Banda or Fiji, where more complex slab geometries or subduction histories would be expected to introduce significant lateral deviatoric stresses [*Hamburger and Isacks*, 1987; *Chiu et al.*, 1991; *Manga et al.*, 1992; *Chatelain et al.*, 1993].

Quarter hemisphere equal-area projections rrf the main slab and isolated earthquake focal mechanism *P* axes, and Anderson-Darling plots and the Anderson-Darling statistic [*Frohlich and Willemann*, 1987], show that the main slab and isolated event axes arc significantly different from isotropic distributions and from each other, the main slab event *P* axes cluster near the downdip directions of the subduction zones studied, and the isolated events have *P* axes which cluster near the normal axes of the subhorizontal deflected slabs,

Stress models of subducting lithosphere indicate that the compressional stress should be parallel to the direction of particle motion, becoming horizontal in models where the lithosphere is deflected [*Vassiliou and Hager*, 1988], in contrast with the vertical compressive stress found for the isolated mantle earthquakes (Figure 2). Fluid mechanical analogues of subduction show (hat in cases of layered convection and retrograde migration of the trench at the surface, the subducting lithosphere reclines to horizontal and rolls back once it reaches the base of the upper mantle [*Kincaid and Olson*, 1987]. The absence of horizontal transmittal of compressive stresses beyond the initial point of deflection (e.g., Izu-Bonin, Banda, and Tonga) argues for little or no horizontal motion of the subducted lithosphere after deflection, in agreement with the general rollo.grade migration of all trench systems of the circum-Pacific [*Garfunkel et al.*, 1986] and with the occurrence of isolated deep earthquakes only on the side of the Wadati-Benioff zone farthest from the trench.

Remnant lithosphere is capable of producing large earthquakes representing a fair proportion of worldwide moment release. The largest known deep earthquakes (Spain, Colombia, Kurile) take place as isolated events, the Spain and Colombia events in extensions of shallower subduction zone seismicity. Their locations indicate that [he physical conditions leading to faulting at depth persist long after the lithosphere has deflected and is residing at the bottom of the upper mantle. The isolated deep earthquakes differ only in their focal mechanism from typical deep events; their large size indicates the presence of large volumes of material still in seismogenic conditions.

While only detailed numerical modeling may provide some definitive explanation, the presence of large deviatoric stresses associated with near-vertical compression suggests that gravitational forces associated with the presence of large volumes of material in nonhydrostatic conditions may be the origin of isolated mantle earthquakes. In turn, this may be related to the accumulation of large deposits of cold lithospheric material which has yet to undergo the phase transition which we observe seismically in the slab core [*Ringwood and Irifune*, 1988; *Kirby et al.*, 1991; *Tackley et al.*, 1993; *Weinstein*, 1993]. The departure from vertical compression observed for a few of the isolated events shows that deviations from the simple model we present do occur which may be due to complexities in particular subduction histories or due to dynamical aspects of the deflection process in different subduction regimes. While continued tomographic and other seismological and numerical studies will clarify our understanding of the fate of subducting lithosphere in the mantle transition zone, the occurrence of isolated deep earthquakes outside the main areas of deep seismicity in half the subduction zones with deep earthquakes indicates that deflection of subducting lithosphere at the base of the upper mantle is a common feature of mantle dynamics.

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D. Giardini, Istituto Nazionale di Geofisica Via Vigna Hurato. 605, Rome, 00143 Italy. (e-mail: internet: giardini@in8800. cincca.it)

P. Lundgren, Jet Propulsion 1 aboratory, California Institute of Technology, 4800 Oak Grove Dri c, MS 183-501, Pasadena CA 91109-8099. (e-mail: internet: paul@arrakis.jpl.nasa.gov)

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